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THE DESIGN OF A TE SUB 13 MODE PHASE LOCKED OSCILLATOR

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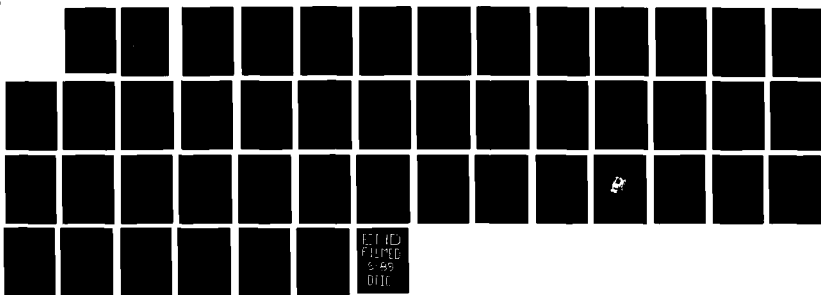
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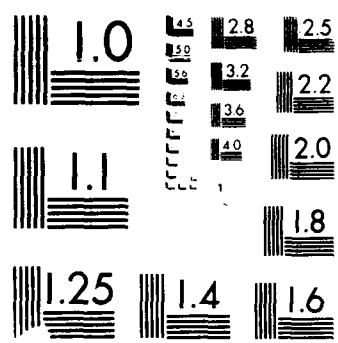
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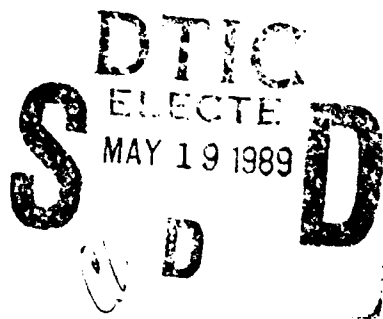
The Design of a TE₁₃ Mode Phase Locked Oscillator

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| <p>The design is presented of a TE₁₃ Mode Phase Locked Gyrotron Oscillator. The oscillator is phase locked by a signal injected into a prebunching cavity. As one extrapolates microwave tube technology to higher power and/or higher frequency, one is ultimately forced to deal with overmoded systems. The design trade-offs are constrained by the overmoded nature of both the oscillator and bunching cavity.</p> | | | | | |
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THE DESIGN OF A TE_{13} MODE PHASE LOCKED OSCILLATOR

I. Introduction

The goal of the low power experiment is to study a phase-locked oscillator in the actual mode at which the high power phase-locked oscillator will run. The phase locking signal will be injected into an input cavity where it will prebunch the beam. The use of a prebunching cavity allows for amplification of the prebunching signal from the first to second cavity. Follow on designs which utilize additional buncher cavities allow for more amplification of the input signal. The mode of operation will be the TE_{13} mode in both the main cavity and in the prebunching cavity. A TE_{13} mode is about as overmoded as seems prudent to operate in a first experiment. Also, a very difficult problem in the design of the experiment is the stabilization of the prebunching cavity. The use of axial slots greatly reduces the cavity Q of all modes but the TE_{1n} modes. Furthermore, a TE_{1n} mode has the additional advantage that it is relatively simple to convert to a fundamental TE_{11} mode which is then quite easy to radiate. This experiment is designed using a thermionic electron beam and will be operable at high rep rate and high average power. The conceptual design of the 85 GHz two cavity phase locked oscillator is shown in Fig 1.

II The Experimental Design

The design is very complicated because both the oscillator and prebunching cavity have had to operate in a very overmoded configuration. Recently, it has been shown that with careful design, a high power free running gyrotron oscillator can operate in a single very high order mode.^{1,2} However, operation as a phase-locked oscillator puts many more constraints on the design than does operation as a free running oscillator. In addition to selecting the proper mode in the oscillator cavity, the phase-locked oscillator must be designed so as to suppress oscillation in the input cavity, launch the proper mode in the input cavity, and suppress communication between the input and oscillator cavities. Furthermore, the length of the drift section between the two cavities is limited by the thermal spread on the beam, as discussed in the previous section and elsewhere.³ For instance, it might be thought that one could always stabilize the prebunching cavity simply by making it short enough. However, if one uses sudden changes in the cavity radius to define the cavity, one can make the cavity very short, but one will have a great deal of mode conversion at the cavity edges. This mode conversion will both lower the Q of the input cavity and also effectively trap any radiation which leaks out of the main oscillator cavity. Alternatively, one could use

gentle tapers to define the cavity. This is, in fact, necessary to minimize mode conversion and our design does incorporate gentle tapers, and so will the gigawatt design. However, now one has fringe fields which extend far into the taper region, so that the effective cavity length is not simply the length of the straight section between the tapers, but is much longer. Even for zero straight section length, the effective length of the prebunching cavity can be considerable.

The longer one makes the taper on the cavity wall, the less mode conversion there will be. However, the taper cannot be made arbitrarily long either. For one thing, this makes the effective length of the prebunching cavity very long, and thereby more difficult to stabilize. Also, a long taper means a long drift section, so that thermal spread on the beam would greatly reduce the phase locking bandwidth. Thus, before the experiment can be set up, it is clear that a very careful, time consuming design is required.

Certain basic principles have become clear as we have proceeded with this design. First of all, our original strategy was to maximize the phase locking bandwidth by maximizing the field in the input cavity. This implied using a fairly high Q cavity for the input, and our original design choice was for a Q of five to ten thousand, not much less than the Ohmic Q . It was

expected that the input cavity would have a lower start oscillation current, but that the input cavity would be stable because the magnetic field would be too high for it to oscillate. That is the input cavity would be very short, so that above a critical field B_0 it would be stable. The main cavity would be longer and would oscillate at higher fields. The start oscillation current for the input cavity and the main cavity as a function of the magnetic field, for our original design, is shown schematically in Fig. 2. One disadvantage of such design is immediately apparent. On the I-B parameter space of a single cavity gyrotron, the regime of most efficient operation is shown in Fig. 3. Clearly, the high Q input cavity does not allow the main cavity to access the regime of most efficient operation. Furthermore, one is in danger of having the input cavity self oscillate due to operating in magnetic fields which are slightly incorrect. Finally it was realized that even though the inherent bandwidth of the oscillator is larger, it is still limited by the low bandwidth of the input cavity.

For all of these reasons, the design was switched to a low Q input cavity design with less inherent locking bandwidth. The I-B parameter space of the phase-locked oscillator with the low Q input cavity is shown schematically in Fig. 4. The operating regime now encompasses the regime of most efficient operation,

and furthermore, there is no danger of the input cavity self oscillating at any magnetic field. While the inherent bandwidth is reduced, it also seems clear, in principle at least, that it can be increased by going to a multi-input-cavity configuration. By injecting the power in the first input cavity, one achieves amplification, so that the field in the second cavity is greater. This amplified field then prebunches the beam for the final oscillator cavity.

The total number of cavities is not limited by the thermal spread on beam; thermal spread on the beam only limits the intercavity spacing. At each intermediate cavity, an amplified field prebunches the beam at higher bunching parameter, so that on exiting one intermediate cavity, the beam effectively has no memory of the bunching in the cavities before. What does limit the number of cavities however is mode conversion. In the oscillator cavity, there is some mode conversion from, for instance, the $TE_{1,1}$ to the $TE_{1,2}$. This $TE_{1,2}$ mode propagates freely through the drift tube and through all of the prebunching cavities. As it passes each prebunching cavity, some of it is reconverted to the $TE_{1,1}$ in the prebunching cavity and is then trapped there. If all prebunching cavities are identical, the same fraction of the leaked out mode is trapped in all prebunching cavities. Specifically, some will be trapped in the first cavity. As long as the power trapped in the first cavity

is significantly less than the injected power, it should work as a multicavity phase-locked oscillator. Once the trapped power becomes comparable to the injected power, phase-locked operation clearly becomes nonviable. Thus, in an overmoded phase-locked oscillator, the mode conversion at the cavity tapers limits the number of prebunching cavities. This is in contrast to a fundamental mode oscillator or amplifier where there is no such limitation. For instance, the SLAC klystron has seven cavities altogether. It is unlikely that a $TE_{1,1}$ phase-locked oscillator could ever have nearly that many. However, it could probably have three, and this would be a potential follow on project to this if there is interest in enhancing the locking bandwidth.

The parameters of the low power oscillator are a frequency of 85 GHz, the operating mode is a $TE_{1,1}$ standing mode, the beam voltage is 70 kV, the current is 6 Amps or less, the output cavity Q is about 2000, the input cavity Q is about 1000, the isolation between the cavities is about 45 dB, the input power, from a Varian 85 GHz EIO is 500-1000 watts, and the output power will be 50-100 kW. The performance of the low power phase-locked oscillator has been examined using both the analytic theory for a $TE_{1,1}$ standing mode, and also the slow time scale theory for a $TE_{1,1}$ rotating mode. The analytic theory gives the result that

$$\frac{\Delta\omega}{\omega} = \frac{0.17 I(\text{Amps})}{E(\text{kV/cm})} (U^2 + V^2)^{1/2}$$

where E is the field in the oscillator cavity. Taking I=4 and E=250, we find that

$$\frac{\Delta\omega}{\omega} = 2.7 \times 10^{-3} (U^2 + V^2)^{1/2}$$

For a beam with no thermal spread, $(U^2 + V^2)$ is a function of two parameters, the frequency mismatch and the field in prebunching cavity S. The parameter S is proportional to the bunching parameter Q_b . The slow time scale code predicts frequency width as a function of bunching parameter Q_b for $m(\gamma\omega - \Omega)r_p / p \cos \alpha_0 = 2$ as shown below:

| Q_b | $\Delta\omega/\omega$ |
|-------|-----------------------|
| 0.25 | 2×10^{-4} |
| 0.5 | 4×10^{-4} |
| 1.0 | 1.1×10^{-3} |

In Fig. 5 is shown a contour plot of $(U^2 + V^2)^{1/2}$. Also shown are the positions of Q_b equal to 0.25, 0.5 and 1.0. Clearly, the analytic theory and the slow time scale code are in reasonable agreement for the low power, 85 GHz phase-locked oscillator experiment.

One of the most important things to quantify in designing the experiment is the mode conversion at the tapers, and equivalently, the cavity Q due to mode conversion. The mode conversion codes available to us did not account for standing modes in either the axial or azimuthal direction. Accordingly, these codes had to be modified to account for the actual mode structure. An example of the design is shown in Fig. 6. There, for a cavity with a straight section length of 0.19 cm, the Q due to mode conversion and the maximum magnetic field for oscillation (B_m) are tabulated as a function of taper length. This latter quantity is calculated using the actual computed axial field profile, as it exists in the cavity and as it spills over into the drift section. There the minimum wall radius is 0.4 cm, and the maximum wall radius is 0.5 cm. Another important factor which contributes to the cavity Q is the slot angle of the cavity. This will be chosen to load down all the competing modes, but to allow the desired TE_{11} mode to be excited, but not self oscillate. The cavity Q as a function of slot angle for the TE_{11} (desired) and TE_{01} , and TE_{21} (main competing) modes is shown in Fig. 7.

Since the input cavities have a large number of requirements regarding mode conversion, slot Q , mode excitation, and overall stability, we have minimized the risks by designing three different input cavities. These will be cold tested and

optimized on the actual experimental setup before it is pumped down. The coupling hole will be machined slightly too small, so that it can be easily enlarged. This cold test will determine the input cavity Q and the coupling from the EIO to the cavity. The coupling hole will be determined so as to optimally match the into the cavity. That is, the contribution to Q arising from the coupling hole will be equal to the contribution to Q from everything else. This will be cold tested on the three cavities. The wall radius, slot angle, effective length and predicted total Q for the three cavities are shown in Figs. 8a, b, and c. At optimal coupling, of course, the actual Q will be half of those values. Also shown are the computed axial field profiles. Notice that the effective length is not that strong a function of the physical length of the straight section of the cavity. The reason is that the evanescent region of the fields extend well into the drift section. Notice that the first cavity, the shortest one, has a very high predicted Q . This might appear incorrect because the large amount of mode conversion in the short taper would imply low Q . However, there is mode conversion at each taper, and it is possible that destructive interference between the forward converted $TE_{1,2}$ mode at the right taper and the backward converted $TE_{1,2}$ mode at the left taper could occur, thereby raising the Q . That is the basis of the design in Fig. 8a and the reason the predicted Q is so high. Whether this will actually work as predicted will be answered in the series of cold

tests. In Fig. 9a, b and c are shown the start oscillation currents of the three cavities for the $TE_{1,3}$ and $TE_{4,2}$ mode. Also shown is the start oscillation of the main oscillator cavities. Clearly there is a large range of currents where the input cavities will not oscillate at any value of magnetic field.

We now turn to the design of the main oscillator cavity. As this cavity will self oscillate at high power, it is particularly important that the mode conversion in the input taper be very small, so that it be isolated from the prebunching cavities. In Fig. 10 is shown the mode conversion from the $TE_{1,3}$ to $TE_{1,2}$ as a function of the input taper length. Also shown is the shift in the peak of the electric field profile. This shift essentially adds on to the physical separation of the two cavities. Since the mode conversion of the $TE_{1,2}$ back to $TE_{1,3}$ in the input cavities is always less than 15 dB (as quantified by the standard mode conversion codes for traveling waves) an input taper length of 0.4 cm will give at least 45 dB of isolation between two cavities. In Fig. (III.11) are shown the wall radius, field amplitude and phase as a function of axial distance for the output cavity.

We now turn to some issues of the mechanical and electrical design of the low power phase-locked oscillator. A mechanical view of the experiment is shown in Fig. 11. Notice that the

input waveguide is pumped out in two places, at its entry to the tube, and also in a special pump out section near the input window. A preferable design would have been not to evacuate the input waveguide at all, but severe mechanical constraints prevents the use of a vacuum window inside the two inch bore of the superconducting magnet. Thus the only option is to put the input window outside of the magnet, and use an additional pumping port on the input waveguide. The electron gun to be used is the Varian VUW 8010 (Seftor) gun. This has been used in many experiments at NRL and is an extremely reliable piece of apparatus with which we have had a great deal of experience. Notice that after the gun, there is a space for the input and output cavity. For each, special cavity holders had to be designed, and the cavities themselves had to be designed to fit into them. The output cavity holder is the much more complicated and expensive holder, and the input cavity is the much more complicated and expensive cavity, for reasons we will go into shortly. There are also two current breaks, the first one, which is inside the magnet must be made of a nonmagnetic material; for the second, which is outside, can be either magnetic or non magnetic. The radiation leaves the tube through a beryllium oxide window.

We now turn to the input cavity. For all input cavities, the outside shape is the same, so the cavity holder is relatively

simple to design. The cavity itself is quite massive. The inside shape is machined to match the design of the inside wall which we have just discussed. Since the cavity is slotted, a thick piece of absorber must be used to absorb any microwave radiation coming out of the slot. This is a piece of ceralloy. Since the dielectric constant of the ceralloy is high, a matching piece of macor is used to eliminate reflections. This matching interface must be an odd number of quarter wavelengths thick. The frequency it is matched to is 92 GHz, the frequency of the TE_{11} mode, the main competing mode. The bandwidth of the macor matching plate gets smaller as its thickness increases. For this reason, the most preferable thickness is one quarter wavelength. At this thickness, it will also be a good absorber for 85 GHz radiation; if the thickness is three quarters of a wavelength, there will be significant reflection there. However, machining such a thin, cylindrical piece of macor could be difficult, and it may be that we will have to settle for a thicker piece. A machine drawing of the input cavity is shown in Fig. 13.

The output cavity holder is one of the most complicated pieces to machine. To see this, note that there are three frequencies in the problem, the EIO frequency, the input cavity frequency, and the output cavity frequency. Clearly, one can only have a phase-locked oscillator if these three frequencies coincide to a very high degree of accuracy. The EIO is

mechanically tuneable over about 2 GHz. The input cavities are not designed to be tuneable, because the complications of hooking up the input microwaves would make a mechanical tuning scheme extremely complicated. Therefore the output cavity must be tuneable, so that all frequencies are tuned to the input cavity. To make the output cavity tunable we have utilized a slotted cavity design. A mechanical pusher compresses the cavity and slightly changes its shape and therefore its frequency (and cavity Q also). This plunger must be vacuum compatible. We have found that the mechanical design of the cavity which provides for reasonable amounts of compression (a few mills) with a reasonable force (a few pounds) is one in which the slots are brought all the way to the end of the cavity. Electrically, it is of course greatly preferable to bring the slots all the way to the narrow end of the cavity where there will be no microwave power. The output cavity holder then must be designed to transmit mechanical force through a vacuum enclosure. The actual transmitter will be a small bellows in the cavity holder which is machined separately from the rest of the cavity holder and welded on. A mechanical drawing of the cavity holder is shown in Fig. 14.

Notice that while the cavity is slotted, the main reason for the slots is not to provide mode control, but to allow for mechanical tuning. We have shown earlier that a $TE_{1,1}$ mode gyrotron at 70 kV can run with little mode competition in an unslotted cavity.² Thus, the output cavity holder has no

provision for using absorbers outside the slots. The actual output cavity, with slots and the axial tapers is three dimensional, and cannot be analyzed economically. What can be analyzed are two two dimensional approximations to it. First, we can use the slotted cavity code to calculate cavity frequency and Q as a function of slot width. The result of this calculation is shown in Fig. 15. Secondly, we can use the tapered cavity code (without slots) to calculate the frequency and Q as the cavity wall pivots about the end of the slots. The result of this calculation is also shown in Fig. 15. Clearly, compression of a few mills will give the sort of tuneability required, while not greatly affecting the Q . A machine drawing of the main oscillator cavity is shown in Fig. 16. Shown in Fig. 17 is a photograph of the input cavity holder, output cavity holder, and output cavity.

Finally, we turn to a discussion of the diagnostics of the low power phase-locked oscillator. Since this is a long pulse repeated experiment which will operate at high data rate, the diagnostics are simpler than in the single shot experiments which will be done at the megawatt and hundreds of megawatt level. A schematic of the diagnostic setup is shown in Fig. 18. The Varian EIO is launched through an isolator into the prebunching cavity of the gyrotron. The reflected power will be monitored. Another portion of the EIO signal will be branched off for

comparison with the gyrotron signal. The two signals are sent through variable attenuators so that the signals are of equal strength. They are then mixed in a balanced mixer, and the difference frequency signal is extracted. If the oscillator is phase-locked, then this signal will be a constant, which can be nulled by the use of a phase shifter in one of the lines. Another diagnostic line will sent the signal from both the EIO and gyrotron to a spectrum analyzer so as to to measure the spectrum of each in phase-locked as well as free running oscillation.

References

1. M. Rhinewine and M.E. Read, "A $TE_{1,3}$ Gyrotron at 85 GHz," Int. J. Electronics 61 (6), p. 729 (1986).
2. K.E. Kreischer and R.J. Temkin, "Single-Mode Operation of a High-Power, Step-Tunable Gyrotron," Phys. Rev. Lett. 59 (5), p. 547 (1987).
3. W.M. Manheimer, "Theory of the multi-cavity phase locked gyrotron oscillator," Int. J. Electronics 63 (1), p. 29 (1987).

IV. Febetron-Gyrotron Slotted Cavity Experiments

An experiment was carried out on the Febetron gyrotron facility to investigate $TE_{1,3}$ operation at 35 GHz through use of axial wall slots in the cavity to suppress competition with "whispering-gallery" modes. An earlier experiment produced 100 MW in a circularly-polarized $TE_{6,2}$ mode, and demonstrated frequency tuning over the range 28 to 49 GHz by operating in a family of $TE_{m,2}$ modes, with the azimuthal index "m" ranging from 4 to 10.¹ This experiment employed a 900 keV, 640 A electron beam, and successfully operated in the $TE_{1,3}$ mode at a power level of 35 MW, using a 2.34-cm-diameter cavity with a pair of opposing 45° axial wall slots. In the absence of slots, significant mode competition was observed from the $TE_{4,2}$ mode, so that stable operation in a circularly-polarized $TE_{1,3}$ mode was not possible. Through use of a cavity with 33° axial wall slots, it was possible to operate in a linearly-polarized $TE_{6,2}$ mode at ~48 GHz, while in the absence of slots it was straightforward to tune the interaction through the $TE_{4,2}$, $TE_{5,2}$, and $TE_{6,2}$ modes. These modes were observed through a gas breakdown technique, that permitted straightforward observation of the azimuthal index of the mode as well as the presence or absence of linear polarization. The results of this research have been accepted for publication in the IEEE Trans. Plasma Sci. A copy of the manuscript is attached as Appendix 5.

PHASE-LOCKED GYROKLYSTRON OSCILLATOR

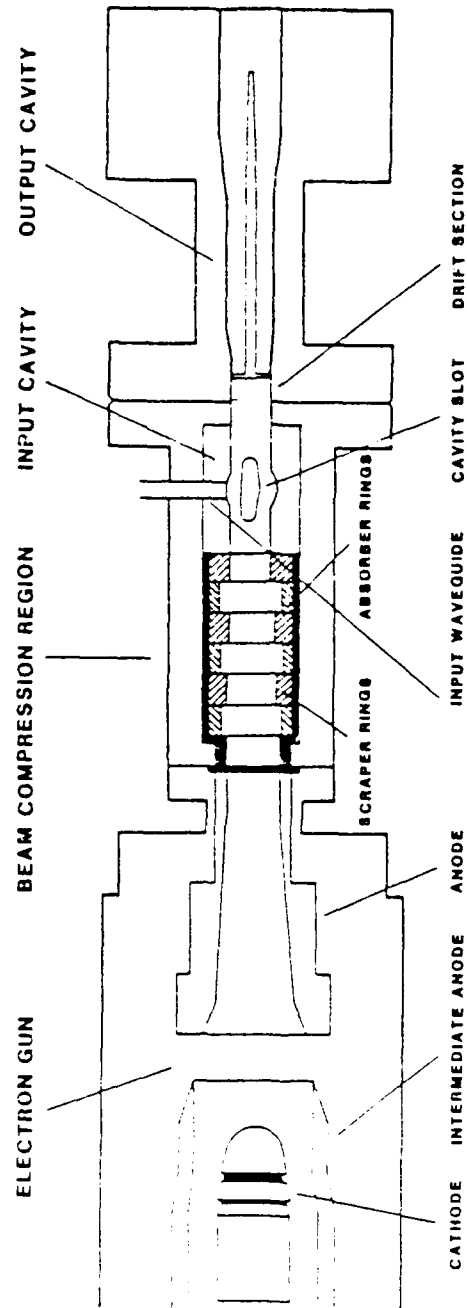
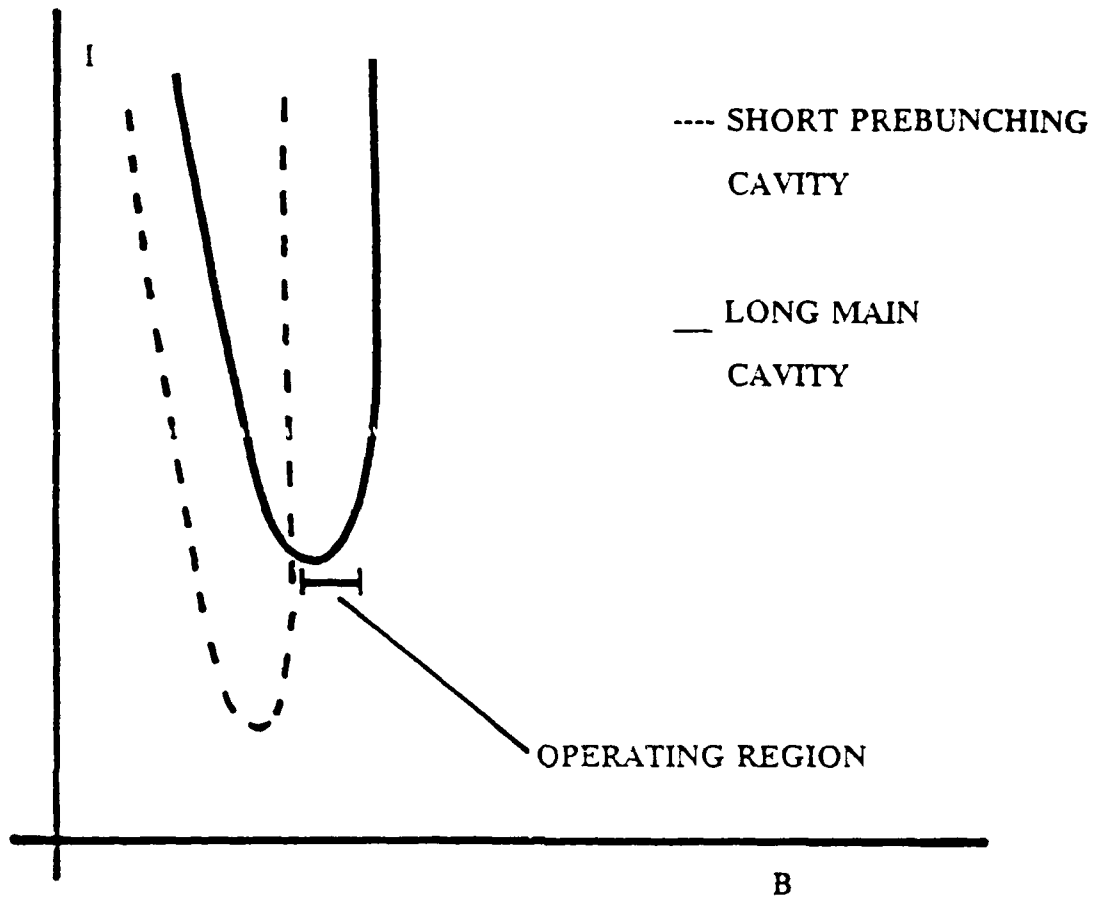


Fig. 1. Schematic of the low power experiment.

ORIGINAL I-B PARAMETER SPACE FOR DOUBLE CAVITY PHASE LOCKED OSCILLATOR



- MAIN CAVITY OPERATES IN LOW EFFICIENCY REGION BECAUSE PREBUNCHING CAVITY HAS LOW THRESHOLD CURRENT BECAUSE OF ITS HIGH Q.
- GETTING A SIZEABLE PARAMETER WINDOW WHERE THE PREBUNCHING CAVITY IS STABLE PROVED VERY DIFFICULT.

Fig. 2. Original high Q input cavity design.

SINGLE CAVITY GYROTRON I-B
PARAMETER SPACE

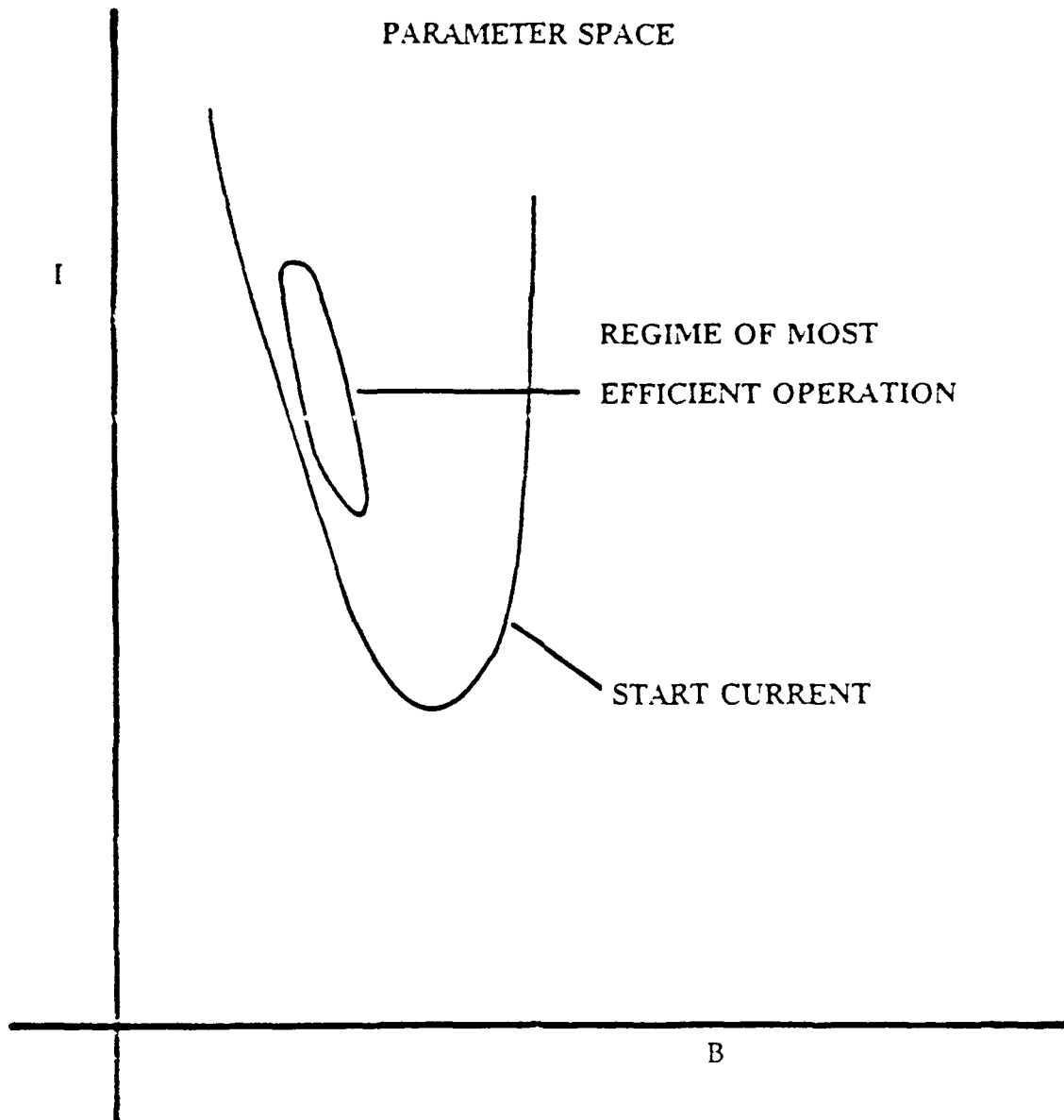
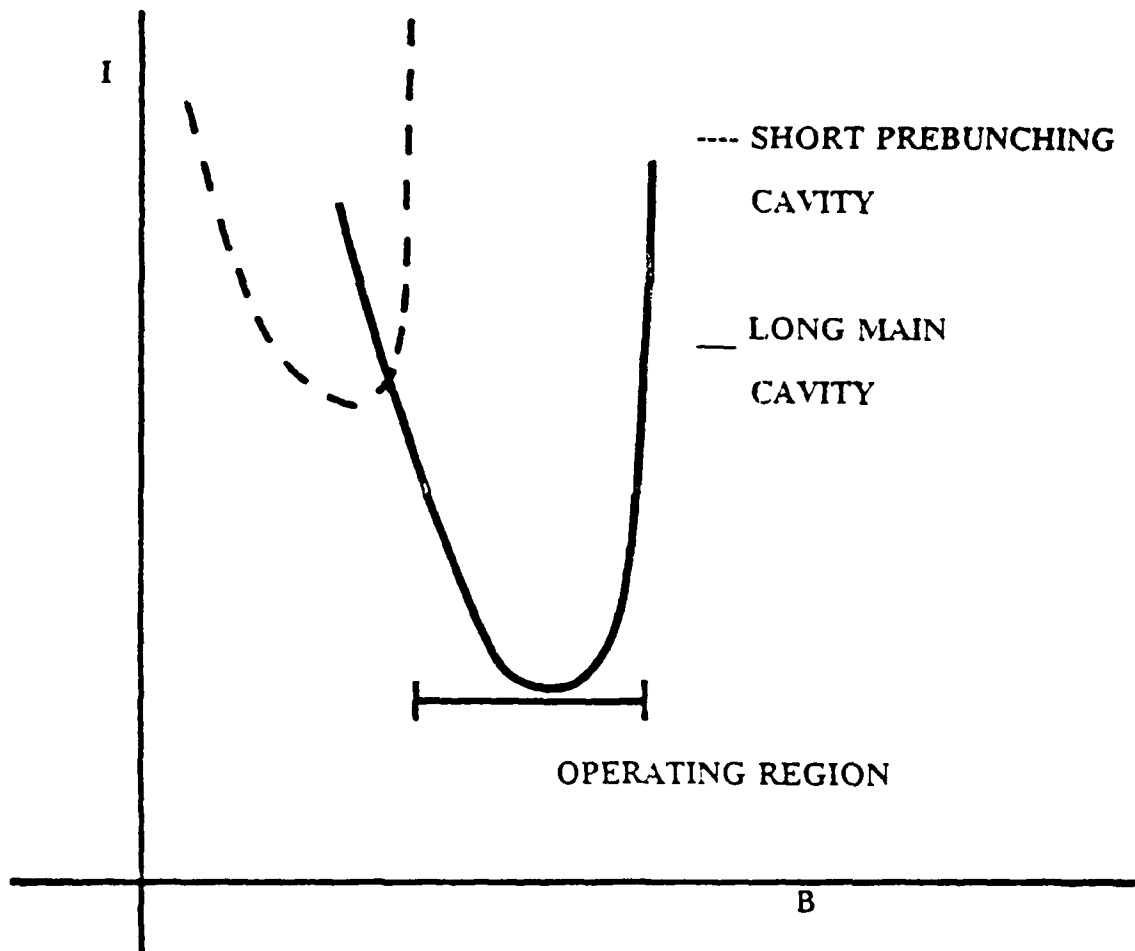


Fig. 3. Operating parameter space for a gyrotron.

I-B PARAMETER SPACE FOR DOUBLE CAVITY REVISED DESIGN OF PHASE LOCKED OSCILLATOR



- OPERATING REGION NOW ENCOMPASSES HIGH EFFICIENCY OPERATION.
- CAN OPERATE BELOW MINIMUM START CURRENT OF PREBUNCHING CAVITY.
- INPUT FIELD CAN BE INCREASED BY GOING TO 3 CAVITIES. THIS SHOULD CONSIDERABLY INCREASE LOCKING BANDWIDTH.

Fig. 4. Revised low Q input cavity design.

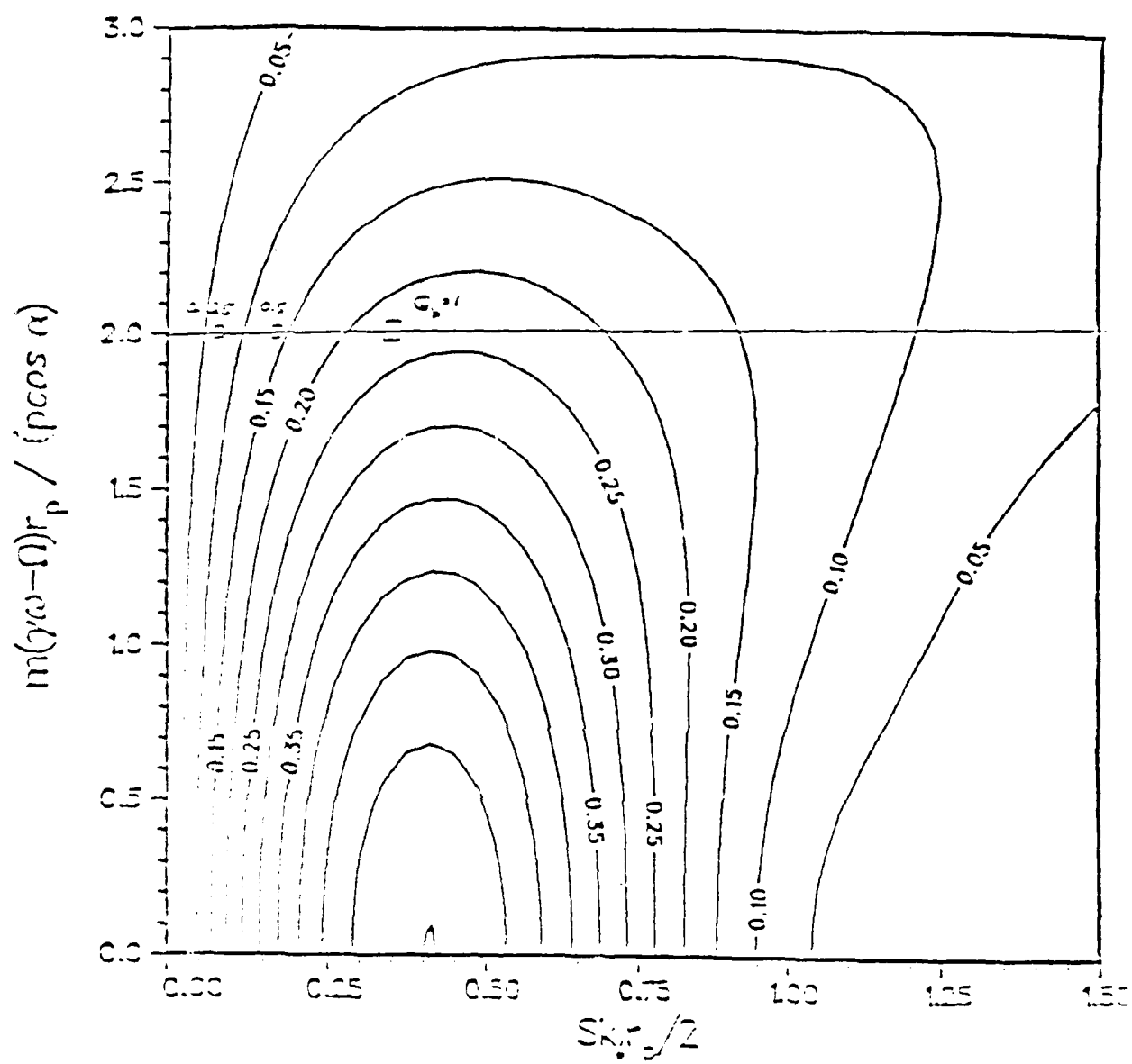


Fig. 3. Contours of $(U^2 + V^2)^{1/2}$. The values of $Q_p = 0.25$, 0.5 and 1.0 correspond to the values of S shown.

Cavity Q Due to Mode Conversion Losses and B_{∞} versus Taper Length

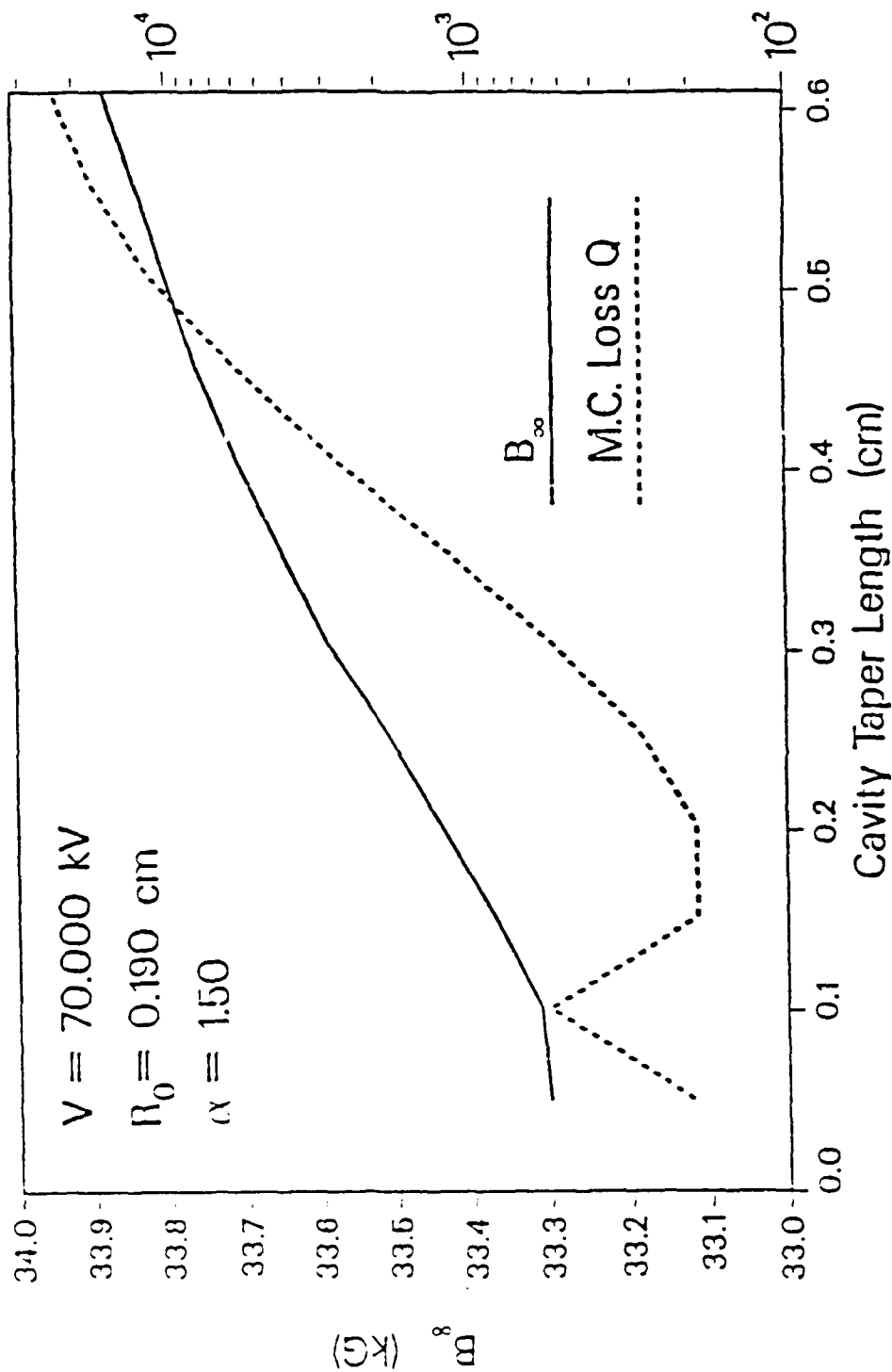


Fig. 6. Mode conversion and critical field as a function of taper length.

Mode Q versus Cavity Slot Full Angle

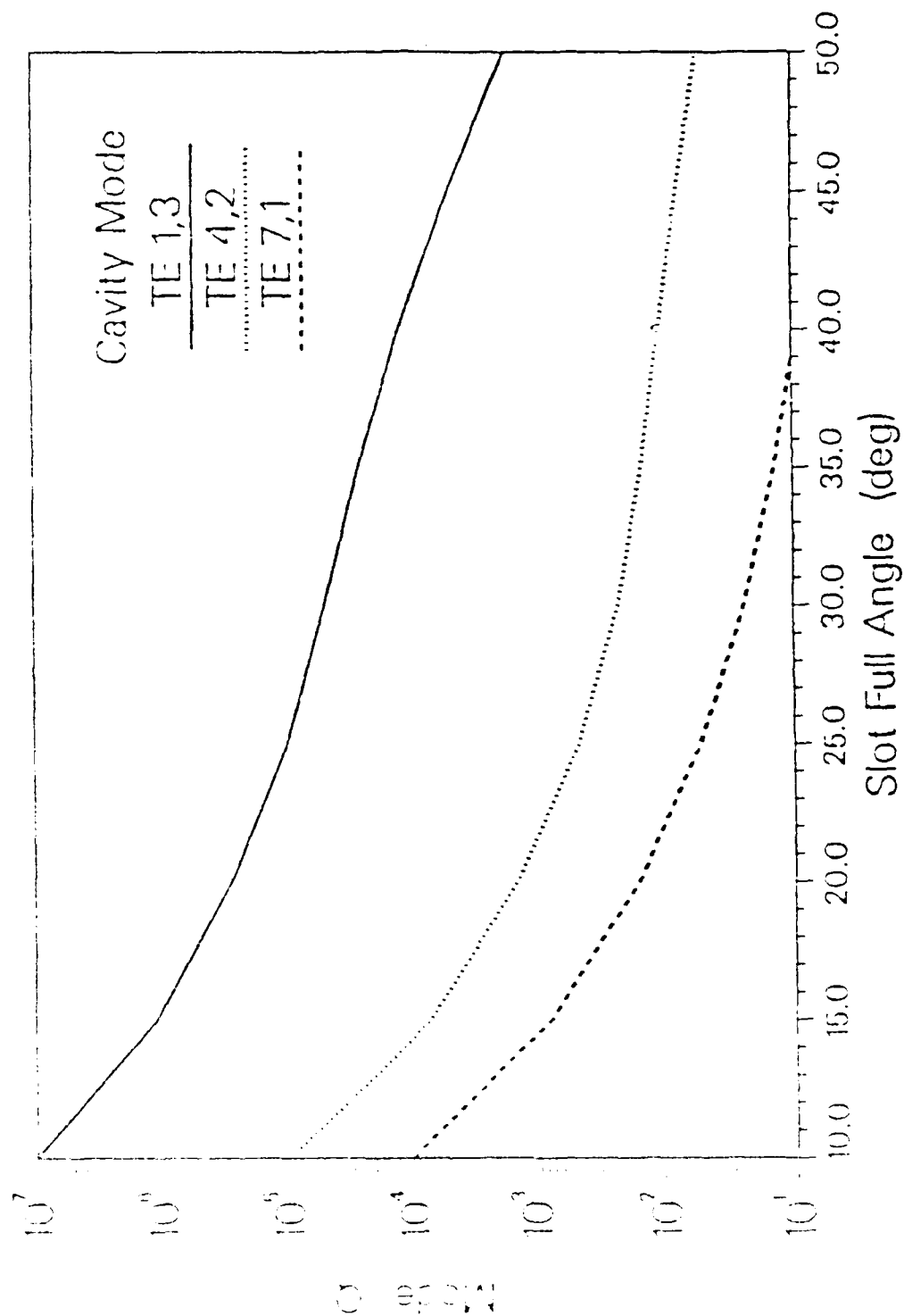


Fig. 7. Slotted cavity Q.

Longitudinal Field Function Amplitude versus Z

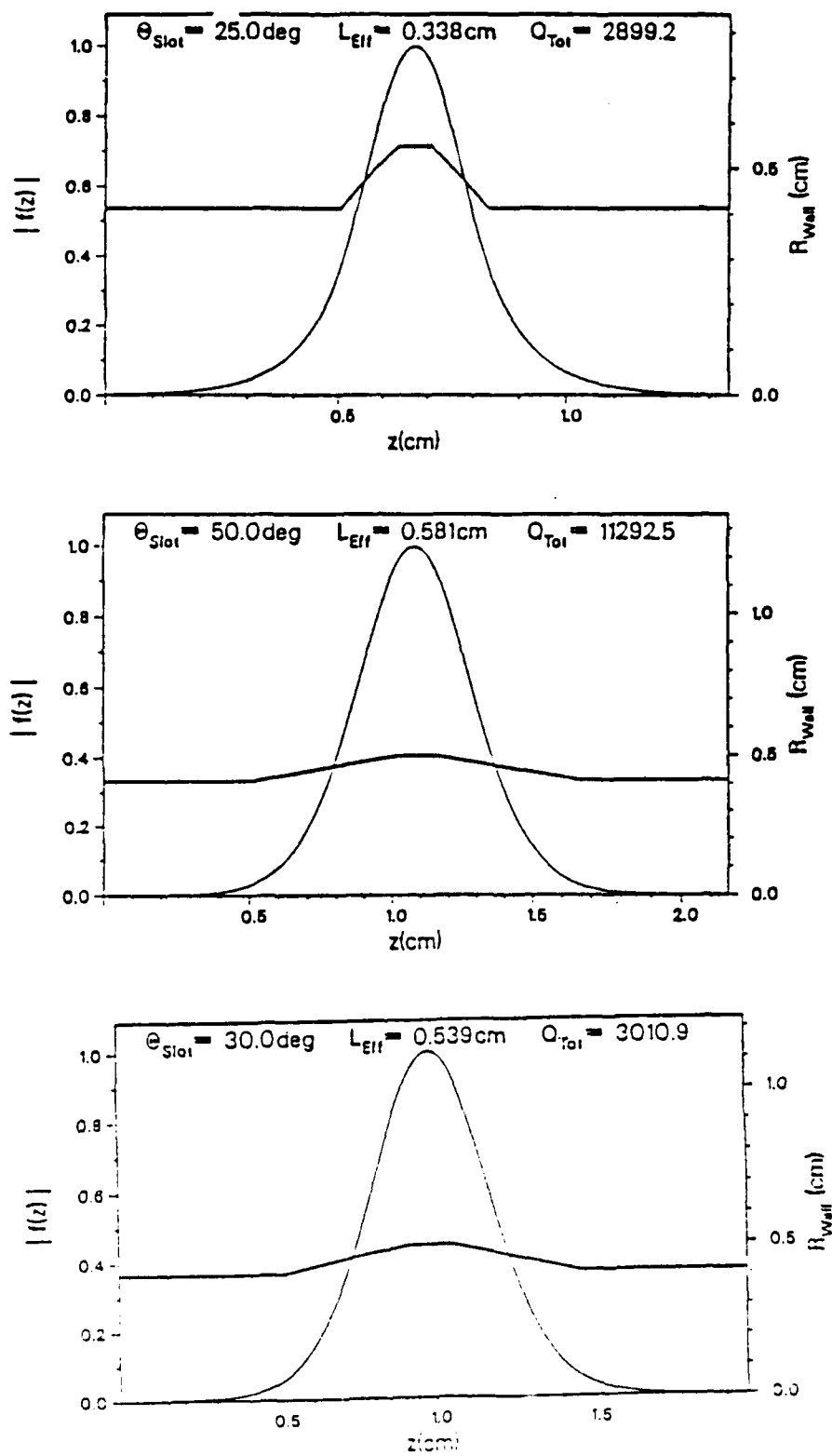


Fig. 8. The three input cavities.

Start Oscillation Current versus Magnetic Field

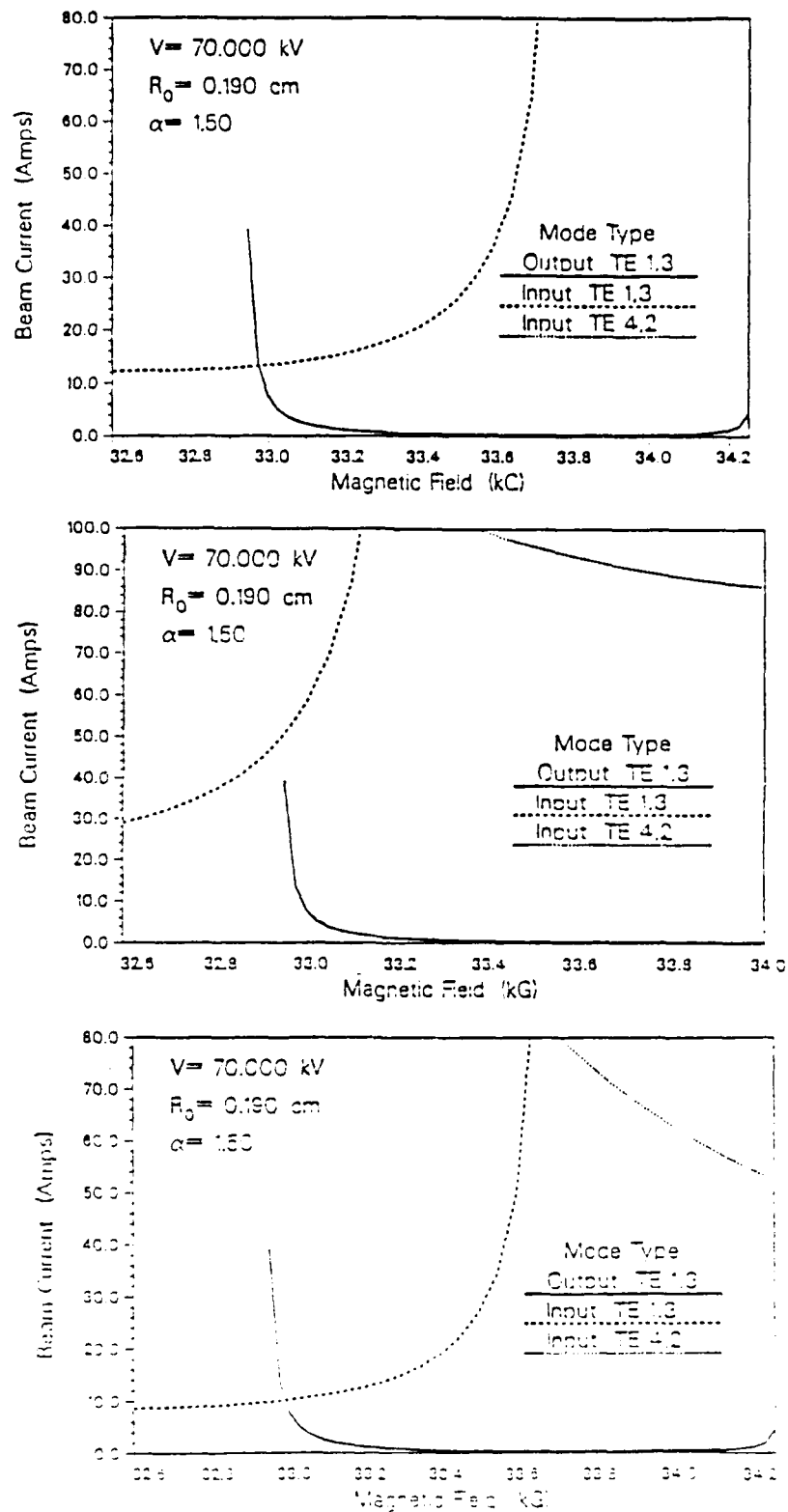


Fig. 9. Start currents for the input cavities.

Backward TE₁₂ Mode Conversion and Profile Shift versus Cavity Taper Length

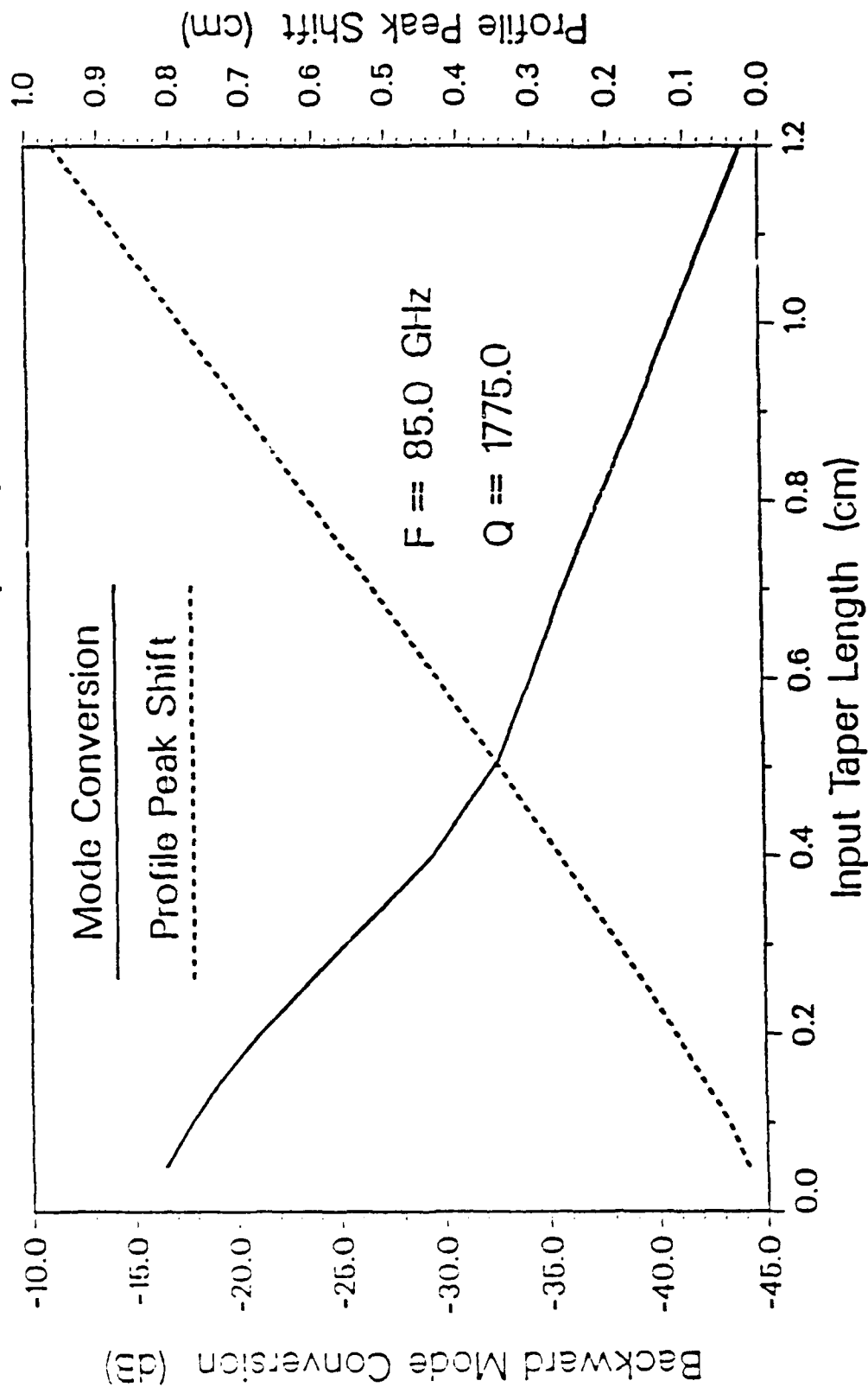


Fig. 10. Mode conversion in oscillator cavity.

Longitudinal Field Function Amplitude and Phase versus z

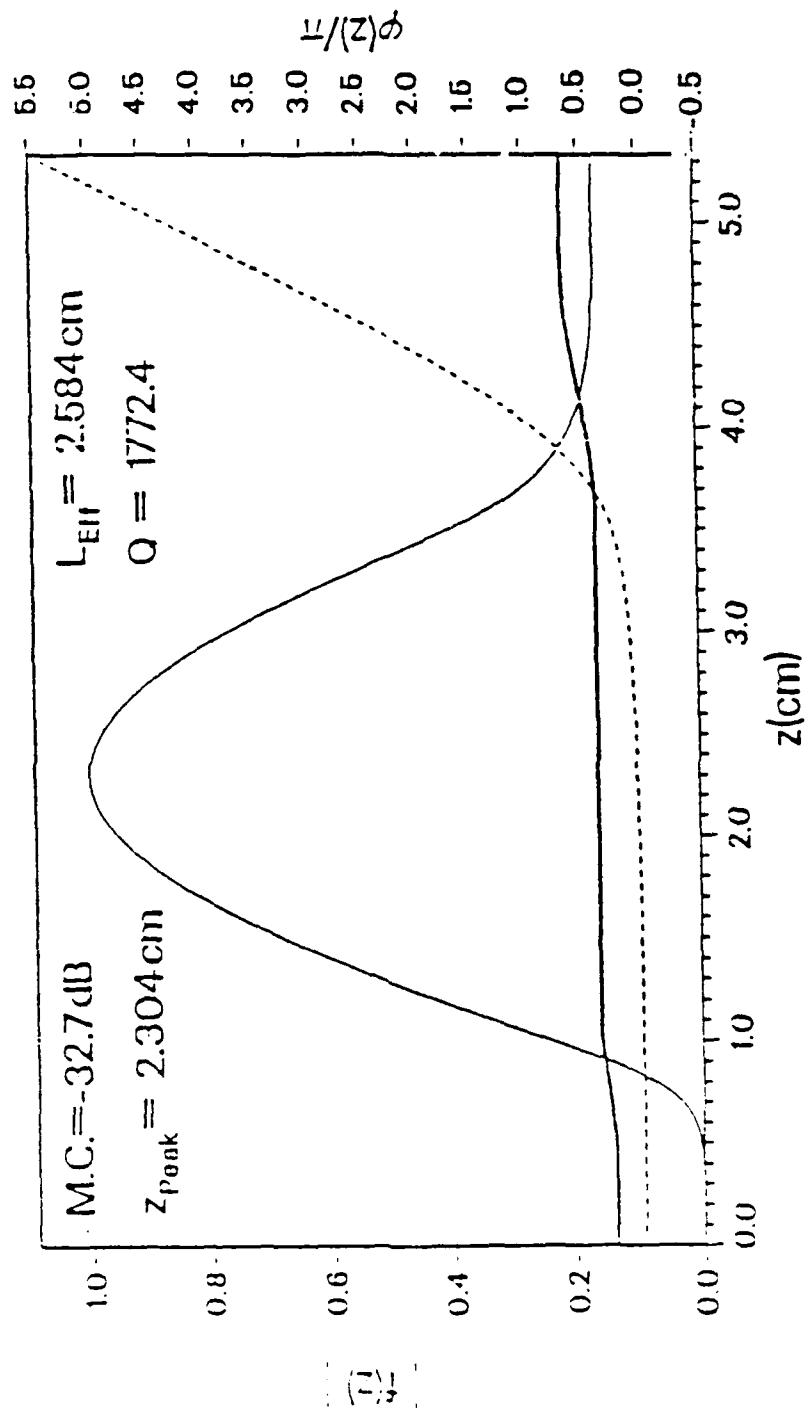


Fig. 11. The oscillator cavity.

TOP VIEW
85 GHz. PHASE-LOCKED GYROTRON
EXPERIMENTAL LAYOUT

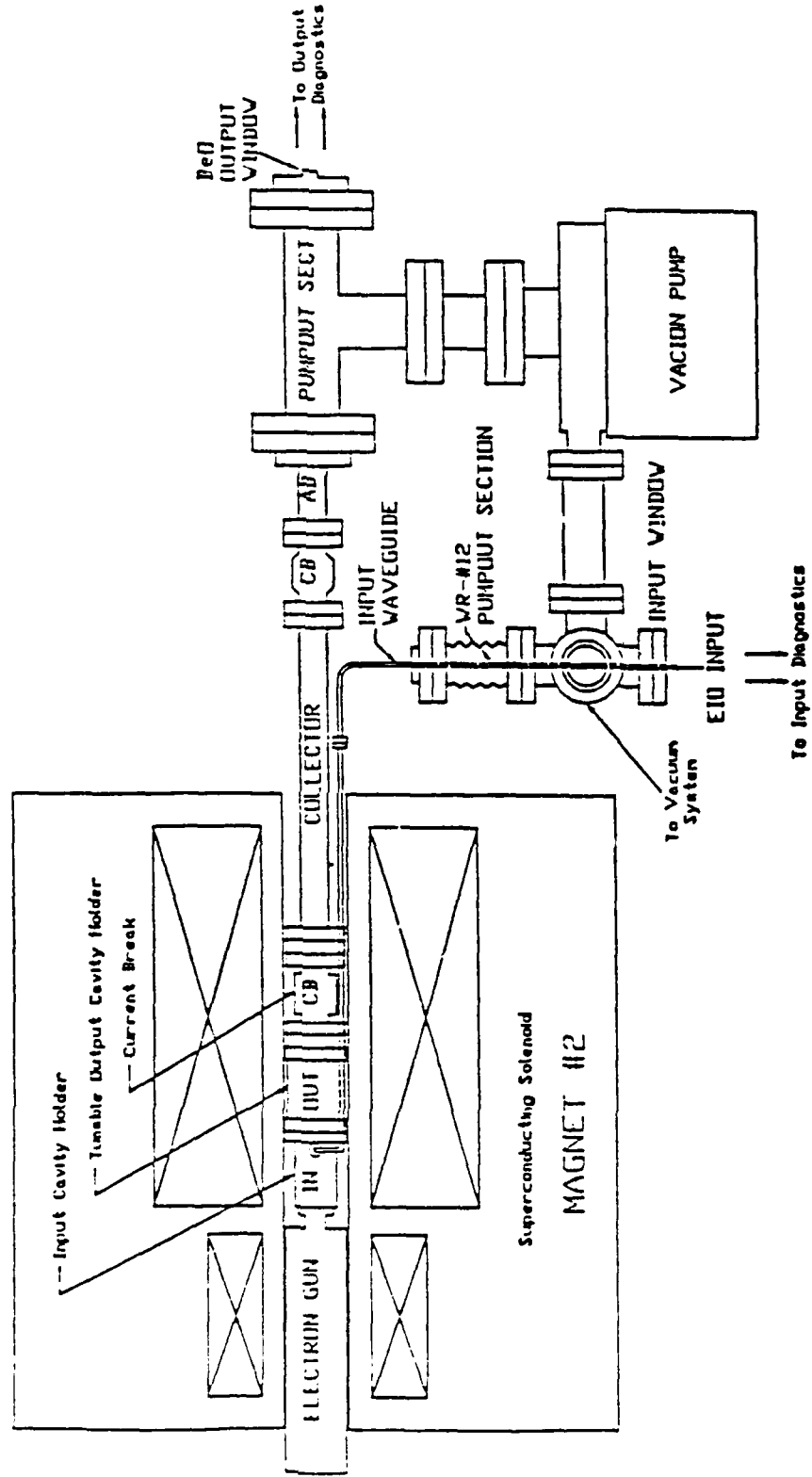


Fig. 12. Mechanical design of the low power phase-locked oscillator.

COPPER INPUT CAVITY

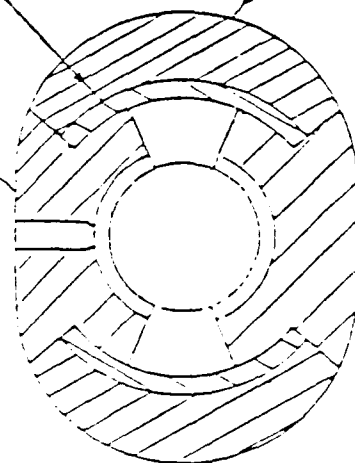
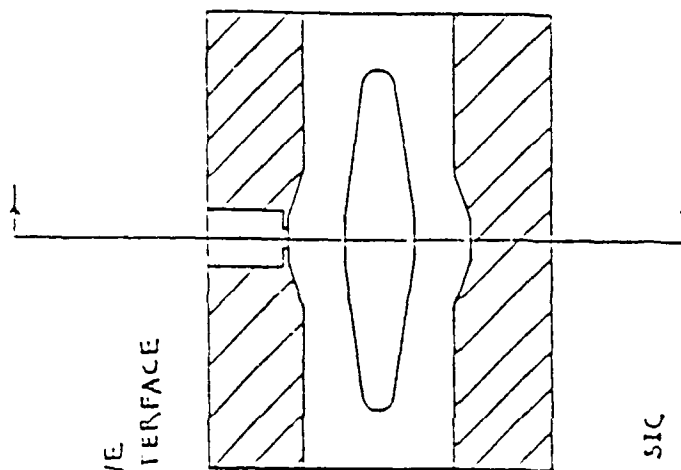
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Fig. 13. The input cavity.

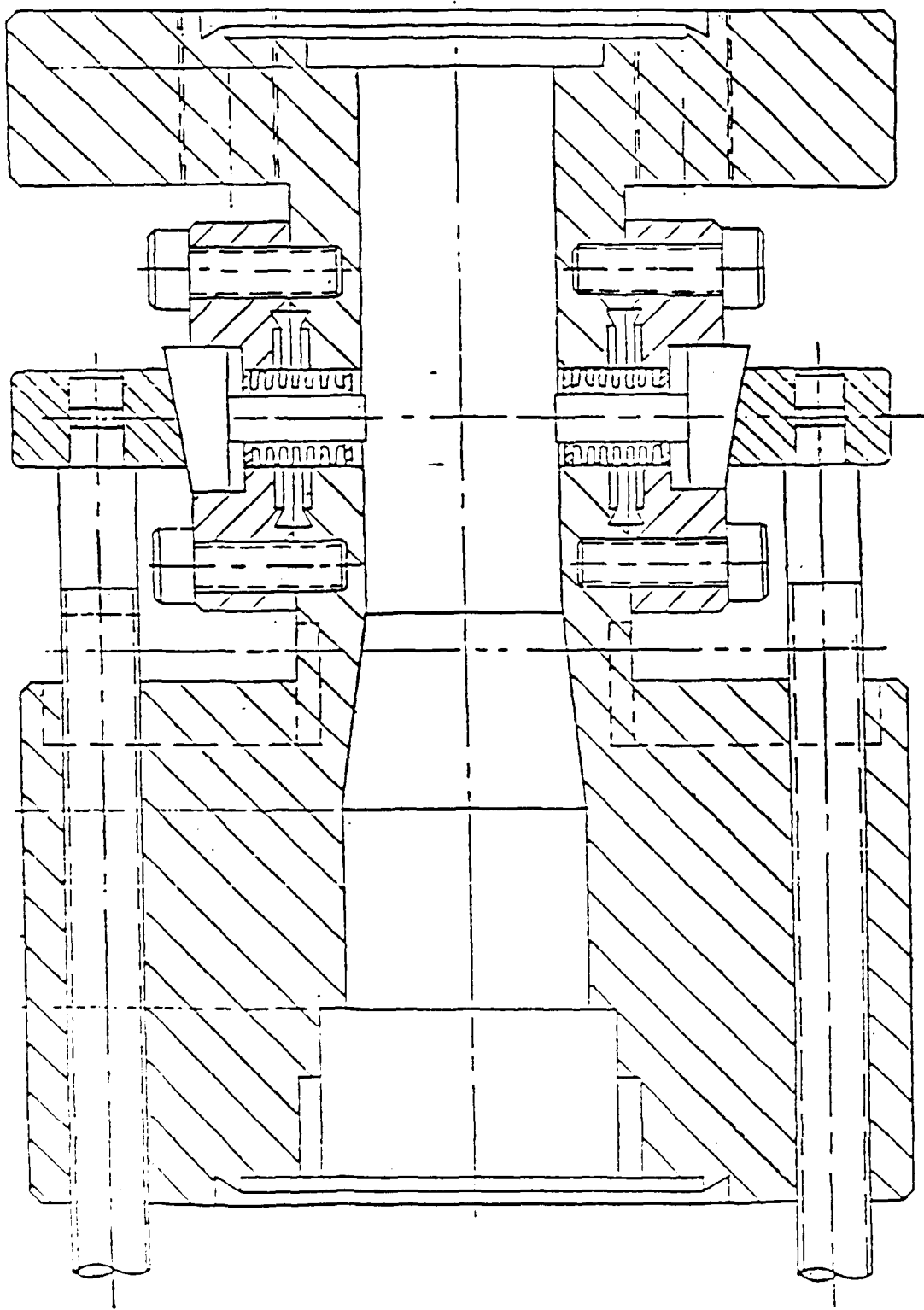


Fig. 14. The output cavity holder.

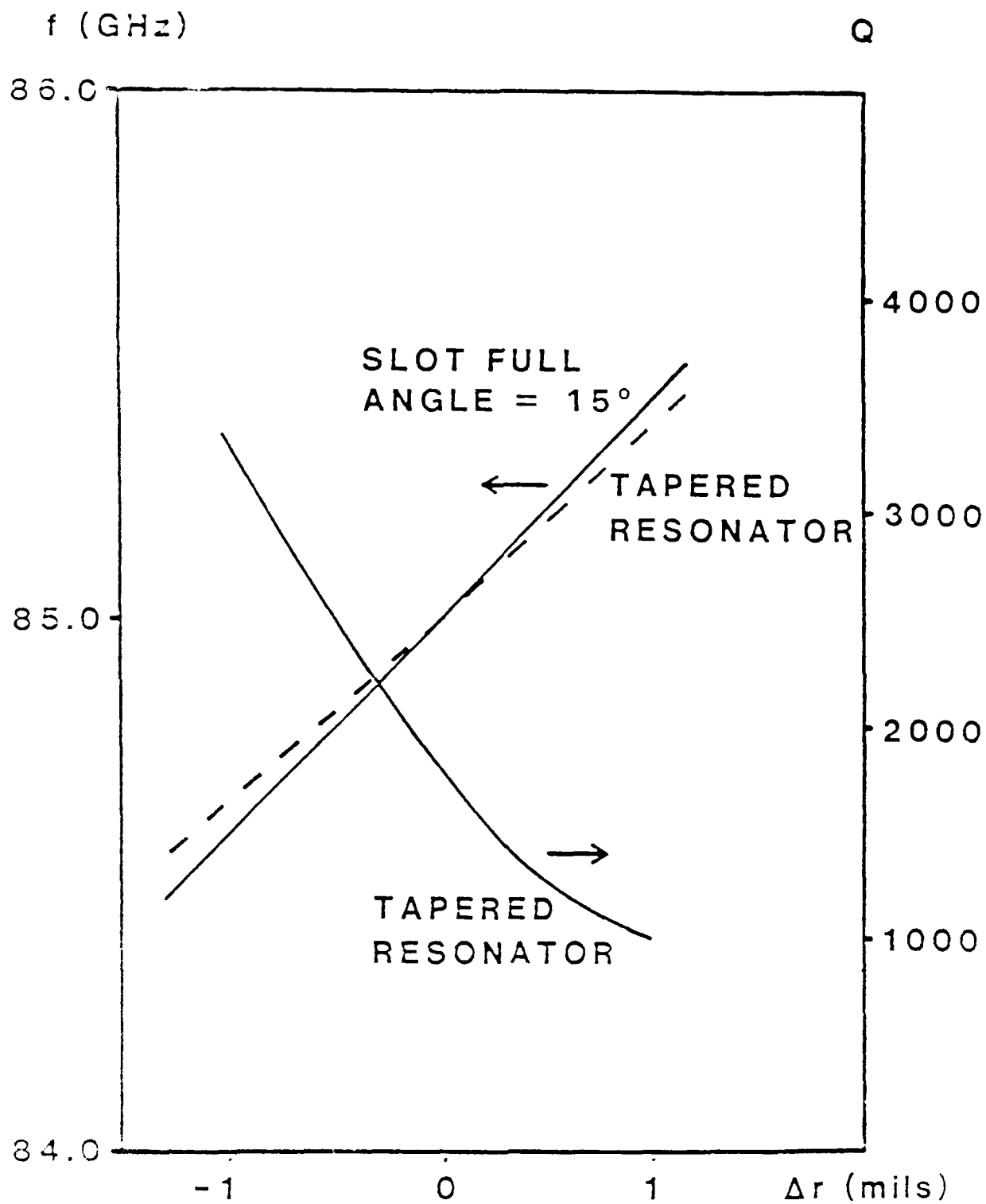
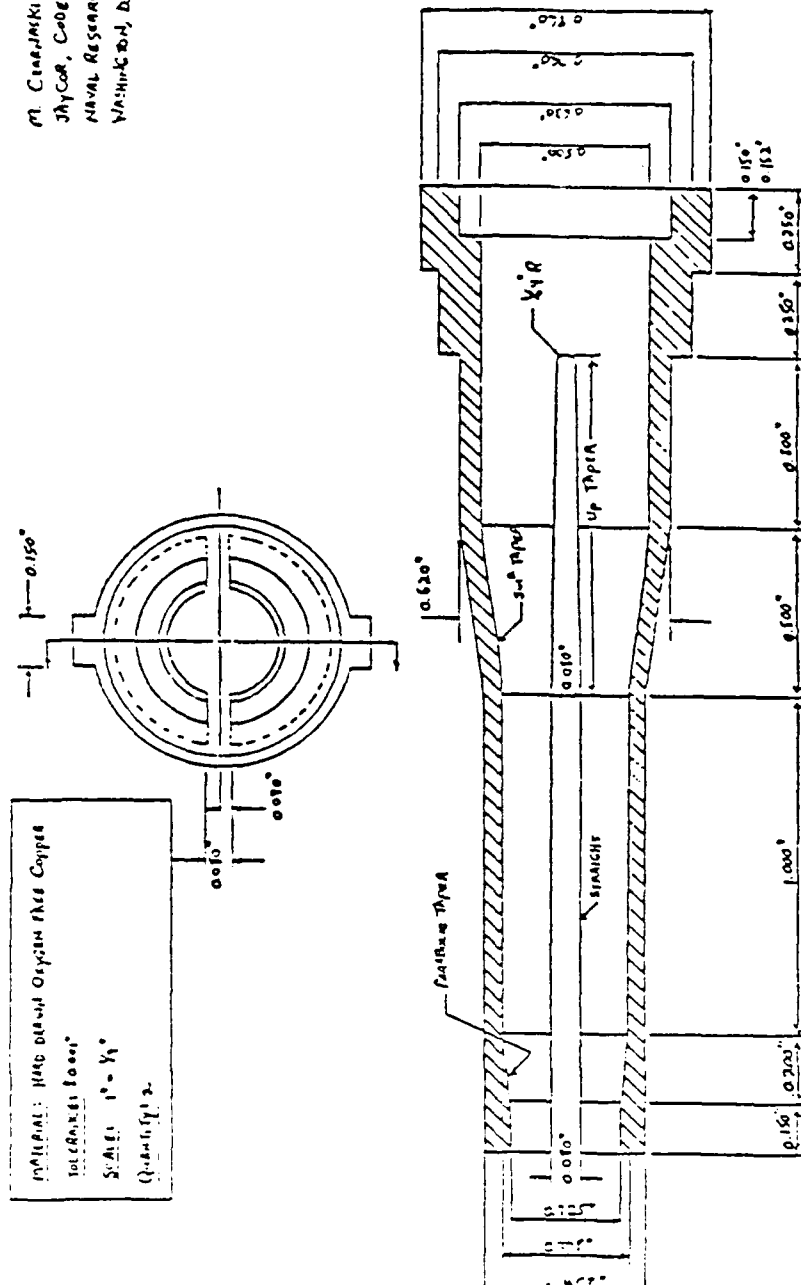


Fig. 15. Frequency as a function of slot width and taper displacement and cavity Q for the tapered cavity.

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Fig. 16. The main oscillator cavity.

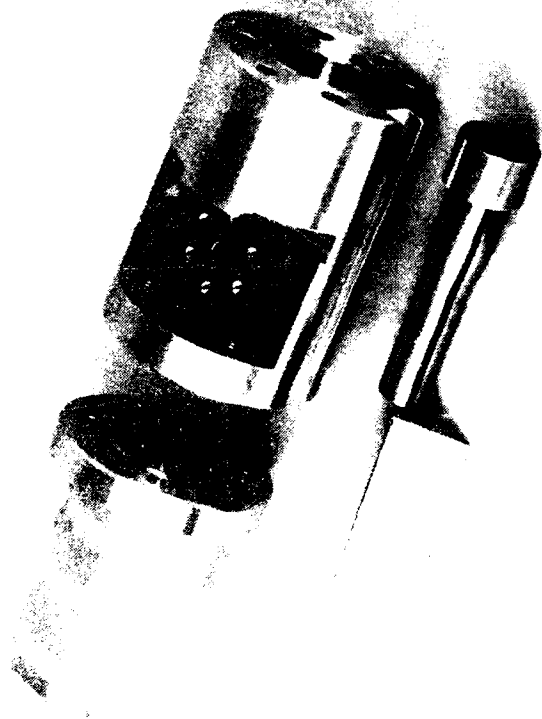


Fig. 17. The input and output cavity holder and the main cavity.

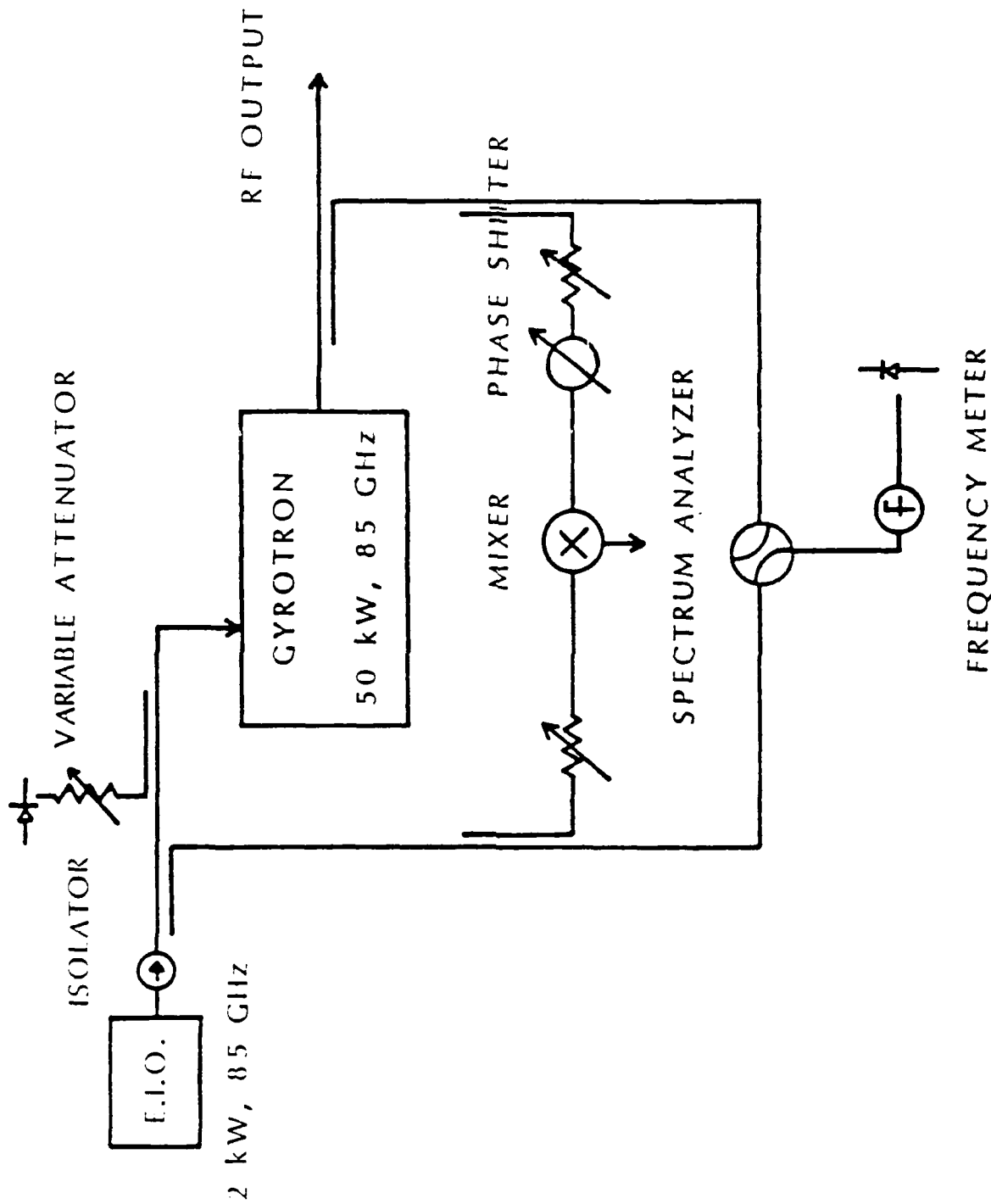


Fig. 18. Schematic of the diagnostic set up.

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